BOREAL ENVIRONMENT RESEARCH 13: 17–32
ISSN 1239-6095 (print) ISSN 1797-2469 (online)

Helsinki 27 February 2008

Economics of alien invasive species management — choices of targets and policies

Ing-Marie Gren

Department of Economics, SLU, P.O. Box 7013, SE-750 07 Uppsala, Sweden (e-mail: Ing-Marie.Gren@ekon.slu.se)

Received 31 Mar. 2007, accepted 28 Nov. 2007 (Editor in charge of this article: Jaana Bäck)

Gren, I.-M. 2008: Economics of alien invasive species management — choices of targets and policies. *Boreal Env. Res.* 13: 17–32.

The purpose of this paper is to present the economic analysis and research on invasive species management, which implies, in principle, a focus on two main questions: (i) how to set targets for species damage mitigation? and (ii) which policy instruments are best in achieving the target(s)? The results indicated that a majority of the studies recognize the need for addressing the links between economic and ecological systems and accounting for the uncertainty associated with predicting damages from invasive species. A common result is that strategies for prevention, control and damage reduction are complementary, and neglect of any of them may lead to unnecessary large social costs. Furthermore, unless economy-wide adjustments are accounted for when designing tariffs on imports, counter-active results may occur where the risk of invasive species damage increases. However, due to insufficient availability of data on the environmental impacts of alien invasive species, there is a lack of empirical applications.

Introduction

Alien species are not a new phenomenon, but can be traced back to the arrival of agriculture 10 000 years ago, which also implied the arrival of pests. Scientists have documented a number of alien and invasive species with detrimental effects. One example is the impact of signal crayfish on endemic noble crayfish in Sweden (Kataria 2007). Another example is provided by the degradation of assets, such as power plants and water treatment facilities, caused by the zebra mussels in the Great Lakes (e.g. Pimentel *et al*. 2001).

However, in spite of ecologists' and biologists' relatively early recognition and concern about environmental damages and social costs associated with invasive species, the environmental economics research on this topic is scant (e.g. Perrings *et al*. 2000). The main part of the economics research has been focused on *ex ante* and *ex post* assessment of costs of invasive species or on cost and benefit calculations of programmes preventing, controlling or eradicating damages from species invasion (*see* reviews in Rockwell 2003, Stutzman *et al*. 2004, Born *et al*. 2005, Olson 2006). Rockwell (2003) and Lovell *et al*. (2006) reviewed studies on damage costs of aquatic alien species, Olson (2006) contains a corresponding survey for terrestrial alien species, and Stutzman *et al*. (2004) and Born *et al*. (2005) provide surveys of studies on damage and mitigation costs of alien species in general. The purpose of this paper is to extend on these surveys by reviewing the economics of management of alien species causing or expected to cause damages in the host regions, denoted as alien invasive species. Alien Invasive Species, or AIS for short, "means an alien species which becomes established in natural or semi-natural ecosystems or habitat, is an agent of change, and threatens native biological diversity" (IUCN 2000). However, a limitation is made by the exclusion of the relatively large literature on pest management, and on economics of infectious disease control in humans and animals.

In principle, the need for management of alien invasive species arises from its public good characteristics. This means that many may suffer from damages caused by alien invasive species escaping from one or several possible transport paths. Correspondingly, costly actions undertaken by one or a few firms will create beneficial changes from reductions in the probability of damages from alien invasive species for several others. Due to this asymmetry in costs and benefits from control, public intervention is needed. Economics of AIS management then deals with two main issues. One is the identification and quantification of targets for projects aimed at applying prevention, control and/or eradication measures at the best use of society's total resources. The other issue is how to choose the best policies for implementing the chosen targets.

The review in this paper shows that the vast majority of studies on economics of alien-species management focus on two main issues: efficient management for target setting, i.e. when expected net benefits for society are maximized, and choices of trade policies for preventing species from entering a host region. The choice of target setting is determined by costs of measures and expected impacts of the AIS at one or several of the stages in the alien species invasion chain: introduction, establishment, spread and damage creation. Prevention measures, such as inspection of vessels, aim at reducing the risk of the entrance of AIS in a host region, and control measures, such as harvesting of an invasive aquatic weed, refer to controlling the spread and damage of an AIS within a region. The literature recommends prevention measures when costs of monitoring and inspecting all entrance points are relatively low and the expected damage and growth in the population of the prevented alien species is high, but suggests control measures when these conditions do not hold. A relative advantage of control measures is that they are directed towards sure invasions. Rapid response to a detected alien species can be justified when there is relatively much information on the risks of the spread and damage of the species. Otherwise, investment in bioeconomic data for obtaining more information on spread and damage of the species can be a better strategy than implementing costly measures for combating potentially harmless alien species.

Once the target has been determined for one or several of the invasion stages, policies for affecting peoples' behaviour need to be implemented. A majority of the studies on policies for alien species management focus on tariffs and inspection of imported goods for preventing species entrance. They do, however, arrive at different conclusions depending on assumptions of economy-wide adjustments to changes in trade policies and of causes of damages of alien species in a host country. Although it seems as if tariffs and inspection policies would reduce imports and associated risk of AIS introduction, damages from AIS may in fact increase as a result of a tariff introduction due to changes in land use. Therefore, policies directed towards control of AIS within a country, such as a suggested system for trading risks in AIS, can be preferred to tariff policies. However, the potential of national policies to combat invasive species have been analysed in relatively few studies. There are also few studies calculating and predicting economic and environmental impacts of alternative measures and policies, which is due to the difficulty of obtaining data of sufficient quality. The difficulty specific to alien invasive species is to obtain data of good quality on environmental impacts of invasive species.

This paper is organized along the two main issues on AIS management, i.e. on determining targets and choosing policies. The first chapter then presents research on setting targets with respect to invasive species and the second chapter presents studies on policy instruments suggested for combating invasive species. Each chapter gives a brief economic theoretical background and then presents associated research. Although the theoretical illustrations presented for each of the two research fields may seem unrealistically simple, they are of practical use since they give guidance to choice of strategies and data needs. The paper ends with a concluding chapter.

How to determine targets for AIS management?

Not every alien needs immediate actions, and economic analyses of costs and benefits from different measures against alien species can therefore be a useful tool for policy makers. This implies the comparison of costs and benefits, and choice of ambition level, or target, for management strategies, i.e. the first question raised in economics of policy analysis. The main principles for choosing the 'right' ambition levels are quite straightforward, but, as will be demonstrated in this chapter, the associated empirical applications are difficult to make due to lack of data.

In economics, the guiding principle for choosing the 'right' ambition level for combating the damages of an alien invasive species (AIS) is determined by maximizing total benefits minus costs of measures against damages of AIS (Fig. 1). Figure 1 is a strongly simplified and stylized presentation, but can be useful for structuring information and data needs.

The total benefit (TB) curve illustrates a common feature of declining benefits of further AIS population reduction, which implies that increases in benefits from additional reductions in a certain AIS population become smaller, the higher the reduction level. For example, for a biodiversity threatening AIS, the risk of threat is likely to increase with the AIS population size. Benefits from a certain AIS reduction, as measured by decreases in threat to biodiversity, are then likely to be higher for higher AIS population levels than for lower ones. The TC curve shows the allocation of different prevention and control measures, such as port inspections and creation of barriers, which minimizes total costs for each reduction in the population. Equivalently, the curve shows the minimum financial resources needed for achieving each reduction level. The minimum financial resources needed for achieving the optimal population reduction level where net benefits are maximised correspond to TC*, which can be paid by public bodies as compensation payments to firms bearing the cost of the measures and/or by the firms undertaking the reduction measures. At N°, TC exceeds TB and population reductions at this or higher levels cause net losses for society and should therefore not be undertaken. Note that all reduction levels below N° generate net benefits for society, but N* gives the largest net benefit.

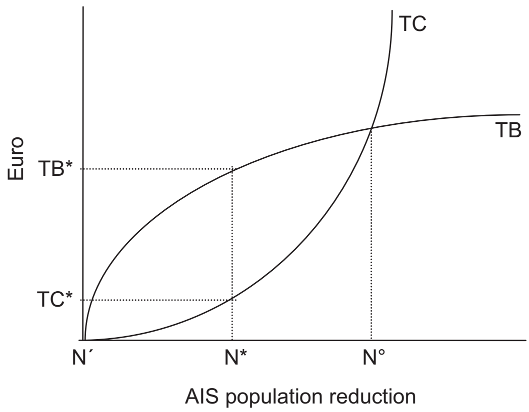

Fig. 1. Illustration of efficient AIS population reduction. The curves TC and TB indicate total costs and total benefits measured in monetary terms (Euro), from AIS population reductions. N´ = no AIS reduction; N* = AIS reduction which gives the maximum net social benefits as TB* – TC*. N° = AIS reduction when TB and TC are equal

The main purpose of most economic studies is to find policies and measures that reach the optimum level of N*. There are several studies estimating costs and benefits of specific measures, such as biological control: *see* e.g. Born *et al*. (2005) and Lovell *et al*. (2006) for reviews. However, although useful, such cost benefit analysis can result in acceptance of any programme generating population reductions between N´ and N° (Fig. 1). The best use of society's total resources occurs only at N* since at this level, society obtains the greatest net benefits. Therefore, the identification and characterization of such an efficient management level are of main concern for most economic studies. It is then recognized that the simple, but illustrative, Fig. 1 hides several factors complicating management in practice. The management arena,

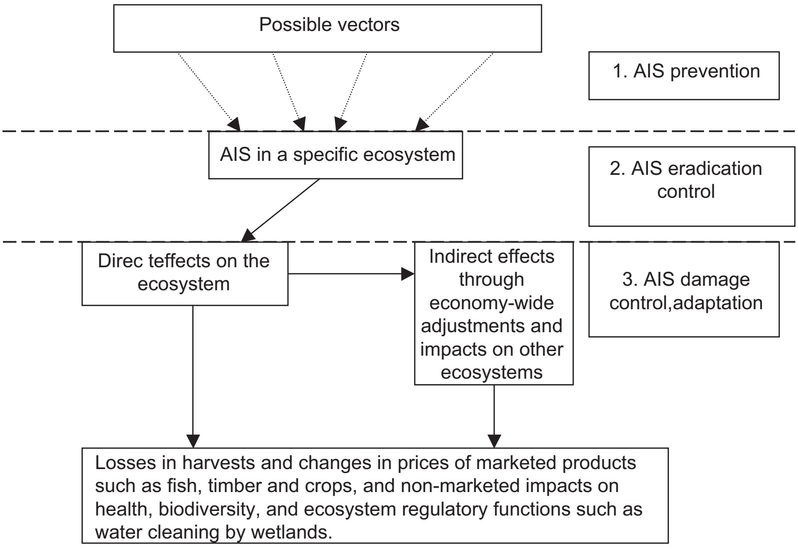

Fig. 2. Illustration of three AIS policy stages in a host region.

encompassing several policy intervention stages between introduction pathways and final possible damages in a region, is illustrated in Fig. 2.

In principle, we can distinguish between three main stages for target setting and policy intervention: introduction, establishment and spread, and damages. Introduction can occur at several entrance points, such as harbour ports, and the risk of introduction increases as the number of ports increases. Each single port has to inspect several vessels, and, as pointed out by Perrings *et al*. (2002), the probability of entrance of an AIS is highly dependent on the weakest link, for example a port with the least stringent inspections of vessels. Measures aimed at reducing the risk of AIS entrance into a region, such as inspection at ports, are denoted prevention measures. If a species is successful in invading a region, the next stage in the chain is to control establishment and spread, which is dependent on several physical and biological characteristics of the region. Examples of control measures are containment, biocontrol, use of chemicals and harvesting of the invasive species.

By definition, an invasive species creates damages, which constitute the third stage in Fig. 2. Damages from AIS are defined as changes in total net welfare in society *caused* by an alien species. Quantification of such a change is obtained in two steps: (i) identification and quantification of all effects, and (ii) assessment of the effects in monetary terms. The first step requires information on the impact of the alien species in humans and on the ecosystem *in situ*, so-called direct impacts, and on surrounding ecosystems and dispersal of effects in the entire economy, denoted as indirect impacts (Fig. 2). Direct effects refer to those occurring directly as a result of the AIS, in an ecosystem such as timber losses in forests, or on human health by, for example, rat bites. Biodiversity changes may also occur in the ecosystem where the AIS enters. Indirect effects occur from the responses of the ecosystems and humans to the direct changes. For example, decreases in harvests of crops or cattle production may affect the food sectors in the economy. Economy-wide adjustments then take place, which result in price increases, which affect consumers negatively. For an exporting country, incomes from international sales decrease. Indirect effects can also occur through the spread of impacts on surrounding ecosystems. For example, an invaded wetland may adjust by reducing its cleaning capacity of pollutants, which affect downstream ecosystems. This may, in turn, give rise to further dispersal of direct and indirect effects through, for example, decreases in fish harvest from a coastal zone which, in turn, affect the fishery sector.

In identifying optimal management, it is not enough just to identify the three policy intervention stages (Fig. 2), but also to understand their dynamics and complexity at each stage. For example, how can the risk associated with each of these stages be described in time and space? This has been recognized in most studies aimed at identifying efficient management strategies. A common feature of these studies is that they are theoretical with no, or only illustrative, empirical applications due to the difficulty of obtaining data on each of the three levels (*see* Fig. 2). This is one reason why a few studies instead focus on cost-effective allocation of different prevention and control measures, where total costs are minimized for different predetermined targets of, for example, AIS spread or damage reduction. Another category of studies analyses the impact on efficient management from insufficient information on the introduction and spread of AIS, and our limited ability to understand small probabilities for an AIS to pass all the stages in the invasion chain, which, if successful, can cause large damages.

Studies on efficient AIS management

A vast majority of the studies on economics of alien species management aim at identifying the optimal management level (N* in Fig. 1), while considering one or several of the stages presented in Fig. 2, and including mainly direct effects. A conceptual model for linking ecological and economic systems for management purposes is provided by Mumford (2002). In the economics literature on efficient management the main focus is on how to make trade-offs between net costs of prevention and control strategies (*see* Fig. 2) (e.g. Settle and Shogren 2002, Perrings *et al*. 2002, Olson and Roy 2005, Perrings 2005, Finnof *et al*. 2005, Finnof *et al*. 2007). While prevention measures allow for relatively low costs of preventing an identified species from entering a host region, relatively much resources may be spent on implementation of measures, such as inspection of vessels, at all possible entrance points. The prevention cost of each identified species may then be relatively large, which can be justified if the costs of controlling the species once it has entered the region are relatively large and/or if the damage costs of the invasive species in the host region are high. The relative advantage of control and adaptation measures is that they are directed towards sure invasions or damage (e.g. Finoff 2007). On the other hand, associated control costs can be large because of the difficulty of reducing the size and spread of the population. However, since complete eradication is usually costly it can be justified on efficiency grounds only for a relatively small population size of invasive species when the growth rate of the species population is high, and marginal benefits from avoided damages are more likely to exceed marginal cost of the control measure (Olson and Roy 2002).

Closely related to choice of strategy with respect to prevention or control targets is the choice of timing of implementation of measures. For example, a rapid response to a detected alien species in a host region may reduce costs of spread and damage as compared with those of delayed control (Settle and Shogren 2002, Saphores and Shogren 2005, Finnoff *et al*. 2007, Keller *et al*. 2007). In principle, there are two balancing factors with respect to the timing of implementation of measures. Delays in control postpone expenses, which then are reduced in present terms when the discount rate is positive. Furthermore, since the damage of the detected alien species is unknown there is a risk of using scarce resources on mitigating a harmless alien species. On the other hand, the risk of irreversible damage from potentially harmful species increases with time. The relative magnitude of these counteracting forces is, however, much determined by the choice of discount rate and knowledge of the detected species. Settle and Shogren (2002) point at the role of hyperbolic discounting (where the discount rate is reduced over time) as compared with a constant rate, which is used in most studies and in practice. Since a hyperbolic discount rate does not discount future net benefits as quickly as a constant discount rate, present value of net utility streams are higher, which favours relatively early actions. Knowledge of potential damage by an alien species can be obtained from investment in collection and analysis of bioeconomic data, which, in turn, can improve the precision of rapid response and reduce costs of mitigating harmless alien species (Saphores and Shogren 2005, Keller *et al*. 2007).

However, there are few studies considering, not only direct effects, but also indirect impacts of invasive species as illustrated in Fig. 2 (Settle and Shogren 2002, Finnof *et al*. 2005). By considering the indirect effects of the invasive lake trout in Yellowstone lake on recreational values and other services provided by endemic species, such as Yellowstone cutthroat trout, Settle and Shogren (2002) show that the level of mitigation measures increases as compared with when only direct effects are included. Similar analysis was carried out by Finnoff *et al*. (2005), but with an application to industry responses to zebra mussels in a Midwestern lake. Firms affected by zebra mussels, such as power plants and water treatment facilities, can apply control and adaptation measures as long as marginal benefits from control are higher than marginal costs. If the policy maker disregards the firms' responses to zebra mussels, social losses occur from insufficient use of firms' resources. Another result is that the policy maker can crowd out the firm's control. That is, by introducing prevention and control, the policy maker can reduce the firm's incentives to implement control and adaptation measures.

How close to the optimal programs (as illustrated in Fig. 1) are then programs implemented in practice? Or to put the question differently, can the framework for choosing targets presented in Fig. 1 be useful in practice when considering the difficulty of obtaining information and data on each of the three policy stages illustrated in Fig. 2? Burnett *et al*. (2006) provide a good example on the usefulness of the framework. They show that actual public spending on prevention and control measures for two invasive species — the weedy shrub Miconia and the brown tree snake — in Hawaii can correspond to approximately 20% of optimal spending. By implementation of an efficient program (as illustrated in Fig. 1), total costs of the two invasive species could be reduced by approximately 90% as compared with those of the actual program. There are two reasons for this difference between actual and efficient public spendings. One is that the magnitude of the actual programme is not large enough to mitigate the spread of species and the other is the inefficient allocation of preventive and control measures. The latter implies that the measures can be reallocated and the same impact on the spread of invasive species can be obtained at a lower total cost.

Management under uncertainty

All the studies referred to earlier treat risk of species invasion with statistical probabilities within an expected utility framework. This means that it is assumed that probabilities for different outcomes of an alien species (Fig. 1) can be identified, and that these can be assessed in monetary terms. There are at least two difficulties with this approach. One is the lack of knowledge with respect to identifying outcomes and risk assessments of, in particular, alien species entering a host region. The other difficulty is that people in general have difficulties in assessing low probabilities with detrimental effects. As noted by, among others, Williamson (1996), there is in general a low probability of establishment, spread and creation of damages for an introduced species. However, once established and spread, the damages of an AIS can be high. Thus, there are low probabilities with potentially large and irreversible damages associated with several invasive species. However, people in general have a tendency to put larger probabilities to detrimental events with large social losses (e.g. Kahneman and Tuersky 1979). This is one reason why expected utility frameworks applied in the studies mentioned earlier may not be suitable for identifying efficient AIS management strategies. Following Knight (1921), we then deal with uncertainty as compared with the case of risk when probabilities can be assessed to different outcomes.

The literature on uncertainty has grown since the identification of the Ellsberg's paradox (Ellsberg 1961). The paradox revealed was that people, in expected utility maximizing frameworks, make irrational choices between lotteries, which are explained by their aversion to uncertainty when probabilities can not be assessed. In such situations, there is a tendency to put higher weights to worst possible outcomes. However, in spite of the specific uncertainties with respect to predicting impacts of an alien species, there are relatively few studies explicitly addressing this problem (Eisworth and van Kooten 2002, Horan *et al*. 2002, Moffitt and Osteen 2006, Moffitt *et al*. 2007). What has then been suggested in this relatively small economics literature on management of alien species under uncertainty? In principle, two ways of dealing with uncertainty have been identified and analysed: to develop methods for obtaining more information or to rely on other decision rules than maximisation of expected utility.

Development of methods for improving data assessment was suggested by Eisworth and van Kooten (2002), who show how expert judgements on effectiveness of different weed control measures can be used for assessing efficient management strategies. Alternative decision models were suggested by Horan *et al*. (2002), Moffit and Osteen, (2006) and Moffitt *et al*. (2007). The potential for alien species management of relatively simple decision rules when probability distributions of different outcomes are not quantified, such as the minimax rule, where actions are taken to minimize social losses from the worst outcome, are discussed in Moffitt and Osteen (2006).

More elaborated alternative decision rules were analysed by Horan *et al*. (2002) and Moffitt *et al*. (2007). Both studies apply pre-invasion control of alien species and rely on probability distributions of different impacts of alien species, but differ with respect to assumptions of manager's decision rules. Horan *et al*. (2002) applied a surprise model where the decision maker is assumed to be uncertainty averse, i.e. welfare decreases from higher uncertainty in desirable outcomes, which implies that events close to the relatively well known events get relatively larger weights than other events. The optimal policy allows for measures affecting relatively low probability of high damage events if they are regarded as possible (low potential surprise), which would not occur within the framework of a traditional risk model. In the Moffitt *et al*. (2007) model, the basic principle is that a policy maker searches for a decision that is robust with respect to as many events, or probability distributions of events, as possible. It is then assumed that events can be characterized by probability distributions, but these are unknown. A robust optimal decision maximizes the range of probability distributions given a certain performance requirement, on, for example, maximum acceptable failure probability of identifying pests. The optimal inspection is then determined by inspection costs and the impacts on the probability for which the model constraints hold.

Cost-effectiveness analysis

Since it is in practice often, but not always, difficult to measure impacts and damages from AIS, and to assess the impacts in monetary terms, it can still be useful for policy making to focus only on cost-effective solutions for predetermined targets, i.e. on the determination on different points on the TC curve (Fig. 1). The policy target can then be determined by political processes, and the task of economic analysis is to identify conditions for when this is fulfilled at minimum costs. The condition for a cost-effective solution is that marginal costs for achieving the target shall be equal for all possible measures. This includes the cost of the measures, such as construction of barrier zones for invasive species, and the impact, which depends on the target formulation. If the target is formulated in terms of risk reductions of species entrance to a certain region, impact assessment is needed on the effect of barrier zones on invasive species risk.

There are a number of studies comparing costs and benefits of different strategies for mitigating damages from AIS (e.g. Anaman *et al*. 1994, Bangsund *et al*. 1999, Cembali *et al*. 2003, McConnachie *et al*. 2003, MacLeod *et al*. 2004, Sharov 2004, Born *et al*. 2005), and the strategies are then ranked with respect to investment and maintenance cost of the measures and sometimes also damage costs of AIS. Such studies are indeed very useful, but they are not applying cost-effectiveness analysis since this requires a predetermined and common target for all measures, which can be expressed in physical or biological terms. Cost-effectiveness analysis then aims at identifying minimum cost solutions for different ambition levels with respect to AIS (TC curve in Fig. 1). Each point on this curve is obtained by calculating and comparing impacts on the target and costs for different prevention and control measures. Usually, depending on the ambition level for the target setting, several measures are used in a cost-effective solution but to different degrees depending on their marginal costs.

There are, however, few studies carrying out a cost-effectiveness analysis with consideration of several measures at different policy stages (Fig. 2) (Leung *et al*. 2002, Buhle *et al*. 2005). A partial cost-effectiveness analysis, which includes several measures at one of the stages shown in Fig. 2, were carried out in more studies, and then in particular, cost effective inspections for prevention of AIS introductions (e.g. Batabyal and Nijkamp 2005, Deangelo *et al*. 2006, Surkov *et al*. 2006). The cost-effectiveness analysis in Leung *et al*. (2002) includes prevention and control measures against damages from zebra mussels in the Great Lakes. The result shows that the optimal payment to the firm for managing zebra mussels would correspond to one third of the actual US budget in 2001 for managing all invaded lakes. It is therefore quite likely that funding for invasive species management is underprovided in the US. Buhle *et al*. (2005) calculated cost-effective solutions for control of a species in different states of the species life cycle and compare measures removing adults *vs*. egg capsules. The results depend on the costs for each measure, and the impact on the growth rate of the species.

Several studies present a partial cost-effectiveness analysis mainly of different inspection schemes for preventing alien species entrance into a country (e.g. Batabyal and Nijkamp 2005, Deangelo *et al*. 2006, Surkov *et al*. 2006, Batabyal 2007). Batabyal and Nijkamp (2005) compared costs between inspection strategies which either inspect cargos upon arrival of a certain number of containers or inspect cargos at fixed time points. They find that the first policy is always less costly than the second. Deangelo *et al*. (2006) compared two inspection schemes which differ with respect to precision and costs, where costs are determined as average waiting time for a vessel, for detecting alien species in cargos. Surkov *et al*. (2006) identified cost effective allocations of inspection among goods and countries where a quarantine agency minimizes total costs for not exceeding certain risks of infested ornaments imported to the Netherlands. In the case of a constraint of total risk, funding should be allocated among inspections of goods from different countries where marginal costs for a given risk reduction are equal, which constitutes the minimum cost solution. Batabyal (2007) arrived at similar conclusions for inspection of ships which should be allocated among vessels where marginal costs for decreasing environmental damage are equal.

Policies for combating damages of alien species

When targets have been determined, the chosen package of measures remains to be implemented. How then to make firms and households implement low-cost measures against damages from alien species so the target(s) is achieved? When designing appropriate policy instrument(s) additional costs occur for implementing and enforcing the chosen instruments, so called transaction costs, which implies that the costs for achieving different AIS reduction targets (TC curve in Fig. 1) increase. Furthermore, not all instruments will generate the minimum cost solutions for choices of measures, which generate further increases in the total costs. This has been recognised in the literature on environmental policy instruments for decades, and this chapter starts with a brief presentation of these experiences. Since relatively many studies on policies for combating invasive alien species are focused on preventing the introduction of AIS by means of tariffs on imports, which is an important vector for AIS, they are presented separately.

Choice of policy instruments

Introduction of aliens by trade can be counteracted by port inspections and quarantine requirements of imported potential AIS, by affecting demand for goods having a high risk of carrying AIS by, for example, labelling, and by importing goods from relatively risk-free regions. Other mechanisms are implementation of policy instruments, such as charges on imports of potential AIS or compensation payments for building barrier zones. Starting in the early 1930s, the literature on the design of environmental policies has developed rapidly (*see* Helfand *et al.* 2002, for a review). One prerequisite for a well-functioning policy, in addition to understanding the causes and damages of alien species, is to identify which criteria the policy instruments are supposed to achieve. Common criteria used for policy analyses are:

- cost effectiveness and technological development, which means that the instruments should generate determined target(s) at minimum cost in the short and long run by stimulating technological development,
- equity and fairness, implying that agreements should result in equal relative cost burdens among the partners and adopt the polluter pay principle,
- precision and flexibility, the instrument should result in actions as close to the target as possible, but at the same time be flexible enough to give the opportunity of changing targets if found necessary in an environmental perspective, i.e. adaptive management,
- enforcement and transaction costs should be as low as possible, which include, among others, costs of administrating the instrument and enforcing compliance.

Is there any instrument that is best with respect to all these criteria? Unfortunately not, but there are candidates that perform relatively well with respect to several of the criteria. The choice is then in principle between four types of policies: command and control, economic instruments, markets for trading, and information (Table 1).

The command and control policy, which has been much used in practice, implies that a regulator decides which measures, such as technology standards for ballast cleaning or bans on imports of certain exotic species, to implement. Another example of a command and control policy is the widely applied system of requiring authority-approved permits for introducing species. The command and control policy usually generates a certain target at relatively high costs since it gives no room for cost adjustment at the firm level. On the other hand, given that all firms comply with the regulation, the precision is high.

Economic instruments create incentives either to reduce alien spreading activities, such as import charges, or to make it beneficial to adopt cleaning activities, such as subsidies for ballast cleaning. Charge instruments rely on the polluter pay principle, and are also cost-effective since firms have the possibility to adjust their activities according to their prevention or control costs. Furthermore, since it is costly to contribute to the spreading of alien species, incentives exist for finding new prevention, control or damage reduction technologies. However, the precision is relatively low since it is difficult to predict the final outcome from firms' adjustments to the instrument. On the other hand, there is a great degree of flexibility since it is in principle relatively easy to change the charge level, increasing it if the final spreads are too high and vice versa. A disadvantage is that firms' relatively high control costs create incentives for evading charge payments, which in turn implies higher transaction costs than for other instruments. Another

Table 1. Classes of policy instruments and their relative advantages.

Policy instrument	Relative advantages
Economic instruments, such as charges on imports and subsidies on control	Cost-effectiveness, flexibility, technological development, fairness
Command and control instruments, such as bans on imports of alien species and quarantine requirements	Precision, equity
Markets for trading, such as trading in duties for ballast cleaning rights for imports of alien species	Precision, cost-effectiveness, flexibility, fairness
Information, such as campaigns on effects of alien species	Technological development, enforcement

problem associated with liability rules, where firms pay for the damage they create, is to show who is responsible for the damage.

The third option — trading market in, for example, risk of species spread — is a combination of command and control policy and economic instruments where, for example, a maximum spreading probability is set for a specific region and quotas are distributed to all affected firms. The difference as compared with a command and control policy is that these quotas, or permits, can be traded between the firms. This means that firms with high control costs purchase permits and low costs firms sell if the offered price exceeds the corresponding control cost. Thus, cost-effectiveness is achieved through the allocation of control towards low-costs firms. In principle then, the trading market has all the relative advantages attributed to both the command and control and economic instrument systems.

The fourth possibility, dissemination of information on, for example, the risk of spread and damages associated with ornamental exotic plants, appeals to people's concern for the environment. As such, transaction costs are likely to be low. Another type of information is on methods for controlling and eradicating species, which may promote technological development. A disadvantage is that the instrument is likely not to result in sufficient mitigation activities in cases where large efforts with high costs are required.

Trade and tariff policies

Trade within and between countries is regarded as the main vector of invasive species, and regulating this has the potential for reducing risk of species introductions (e.g. Perrings 2000). Despite this insight, there are surprisingly few empirical studies identifying the role of different factors for introduction and spread of alien species (Dalmazzone 2000, Vilà and Pujadas 2001). Dalmazzone (2000) made a statistical test explaining occurrences of alien species in 26 countries by testing two interlinked hypotheses: alien species depend on the openness and/or on the activity of a country. Openness is measured as trade related to total income or gross domestic product (GDP) in an economy, activity level measured as GDP/capita, managed land, and population density. Openness gives rise to imports of alien species and activity may create disturbed spatial areas, making them susceptible to alien species. Using the fraction of alien species to native species as a dependent variable, the results indicate that population density, GDP/capita, and managed land have a significant impact on the relative occurrence of alien species. Interestingly, trade volume shows no significant effect, but instead the duty levels on the imported goods, indicating that it is not the trade volume as such that affects spread of species, but instead the composition of trade products and countries of origin. Vilà and Pujadas (2001) contrasted the results of Dalmazzone (2000) by reporting a positive correlation between imports and frequency of alien species in 28 European and North African countries. In addition, the United Nation's index of human development, which includes education and life expectancy, shows a positive impact on alien species occurrences. However, both studies are made with relatively small samples and the results should therefore be interpreted with much caution.

In contrast to empirical studies of causes of AIS occurrences, there are, within the economics literature on invasive species, relatively many studies on trade-related policies, mainly on economic instrument such as tariffs on imports (e.g. Costello and McAusland 2003, McAusland and Costello 2004, Knowler and Barbier 2005, Margolis *et al.* 2005, Tu *et al.* 2005, Tu and Beghin 2006). A majority of these studies are focused on efficient design of tariffs (Costello and McAusland 2003, McAusland and Costello 2004, Barbier and Knowler 2005, Margolis *et al.* 2005). Another aspect on trade and AIS is provided by considering the side effects of agro-forestry policies in term of increases in AIS risks (Tu *et al.* 2005, Tu and Beghin 2006).

The general principle for efficient design of the tariff level on imported goods is that it shall reflect the damage of associated marginal decrease in the risk of AIS introduction not accounted for in the markets for the goods. However, introduction of tariffs gives rise to adjustments in production and consumption in the host country which may counteract the effects of the tariffs on the risk of species introduction (Costello and McAusland 2003, McAusland and Costello 2004). Costello and McAusland (2003) showed, by means of a simple partial equilibrium model of trade for a small country, that decreased imports of, for example, agricultural primary products as a result of a tariff introduction also lead to more domestic production, which in turn raises susceptibility for species invasion by increases in areas of disturbed land. McAusland and Costello (2004) arrived at similar conclusions but from another perspective. They compare tariffs with a command and control type policy, namely port inspection policies for combating introduction of trade-related invasive species, and show that it can be optimal for a host country to increase its inspection and decrease the tariff in order to counteract higher domestic prices, and thereby reductions in consumer welfare and changes in land use, on rejected import goods. When there are several trading partners, the importing country can set an optimal policy based on differences in infection rates between the countries, which would also promote technological development of cleaning measures at the firm level. However, such a discriminatory policy among countries may be difficult to implement in practice due to current WTO (World Trade Organization) regulations (*see* e.g. Perrings *et al*. 2005)

There may be other reasons for undesirable results from tariffs on imported goods than economy wide adjustments (Knowler and Barbier 2005, Margolis *et al*. 2005). Knowler and Barbier (2005) showed that firms' responses to a tax on detected exotic plants may increase the risk of invasion. The reason is that industry managers want to speed up the establishment of nurseries in order to exploit profits before detected invasion, which implies increase in risk of damage during time. They also show that a command and control policy, bans of trade, is more costly than a tax policy. Margolis *et al*. (2005) focused on the role of lobbying by interest groups, which is common in practice, for tariff design. If private lobbying groups can affect governmental behaviour by donations to, for example, election campaigns, they may influence the level of the tariff to their advantages. Trade distorting tariffs may then exist when governments put relatively high weights to private interests, which, in turn, may have a positive impact by reducing the risk of species invasion from trade. This occurs when tariffs are raised on goods with relatively high invasion risk.

However, trade and trade policies affect risk invasion, not only directly through imports of goods with high infestation rates, but also indirectly through changes in the trade structure (Tu *et al*. 2005, Tu and Beghin 2006). Tu *et al*. (2005) looked at the interaction between tariff escalation on agro-forestry markets, which occurs in developed and developing countries, and invasive risk. By means of a simple model of a small open economy, they show that the tariff escalation in agro-forestry products leads to increased risk for species of invasion in developed countries due to the direction in trade towards primary products and decreases in imports of processed goods. The increased risk of invasion can be avoided by lowering tariffs on processed goods. A second benefit then arises from reductions in trade distortions. An expansion on this theme is made by Tu and Beghin *et al*. (2006) by accounting for trades between countries and multilateral trade. They showed that the risk for AIS invasion is likely to increase due to higher domestic production caused by expansion of the export markets. Trade in general makes use of countries' relative advantages which expand export markets and increase the total production from all countries, which results in higher risk of AIS from both increased trade and from larger domestic production.

Non-trade policies

In spite of the difficulties provided by WTO for introducing tariff policies for single countries, there are few studies analysing policies that are not related to international trade of goods and services (Thomas and Randall 2000, Settle and Shogren 2002, Jetter *et al*. 2003, Finnoff *et al*. 2005, Horan and Lupi 2005, Roti Jones and Corona 2008). One obvious question is if policies should be implemented for controlling spread or damage of the species. A majority of the studies raising this issue suggests alternative policies for controlling invasive species; compensation payments for control measures, trading market system and charges on ballast water for vessels (Jetter 2003, Horan and Lupi 2005, Roti Jones and Corona 2008). One study investigates policies directed towards damage reduction by liability rules (Thomas and Randall 2000).

Both systems of compensation payments for implementation of measures and payments for AIS spread and damage create incentives for firm to undertake actions. One main difference between the two types of systems is the relatively ease of identifying firms implementing measures as compared to those responsible for AIS spread and damage. This was considered by Jetter *et al.* (2003) who suggested a compensation system for control programmes of yellow starthistle. They found that farmers had no incentives to invest in control programmes since associated costs exceed benefits from improved land productivity, and a compensation payment was therefore needed to encourage the farmers to reduce the risk of spread of the weed.

Charges, permit market system and liability rules aim at reducing AIS spread and damage by requiring payments from the responsible actors. One difficulty with this approach is to relate a certain firm, or a vessel, to spread or damage of AIS. This is likely to imply the existence of asymmetric information among involved policy makers and firms or households. For example, firms know more about their costs for measures, and policy makers may have specific biological expert knowledge. The existence of such asymmetric information implies that it becomes more difficult to determine the charge or compensation rates, and firms can under such conditions make use of their greater knowledge to their advantage, resulting in less native species protection. This problem has been recognized by Randall and Thomas (2000), Horan and Lupi (2005), and Roti Jones and Corona (2008) when designing their three different systems; damage liability rules, market for risk trading, and charges on risk.

A damage liability scheme is suggested by Thomas and Randall (2000), where a firm is required to post an *ex ante* assurance bond in order to avoid large social losses from species release which the firm can not pay *ex post*. The authors show that if the policy maker imposes a payment requirement that corresponds to the largest possible environmental damage, efficient outcomes can occur. Instead of damage control, i.e. stage three in Fig. 2, Horan and Lupi (2005), and Roti Jones and Corona (2008) focused on control of AIS spread as illustrated by the second stage in Fig. 2. Both studies also applied the instruments to risks of AIS spread by vessels.

A system for trading in risks of AIS on a market was suggested in Horan and Lupi (2005) where vessels operating, for example, the Great Lakes trade in their probabilities of invasions (which is most close to associated environmental damage) on a one-to-one basis. The suggested system is applied to trading in risks for introduction of Ponto-Caspian species in the Great Lakes. Four different policies for ballast cleaning are then compared with the least costly solution: trading (on a one-to-one basis), and uniform requirements on either filtering, heat or ballast exchange. For a given risk target, trading is always less costly than the other systems since it allows for firms to choose the least costly option. Roti Jonas and Corona (2007) suggested another economic instrument; a charge based on changes in total AIS population in a port. In doing this they draw on the experiences from the so-called non-point source literature, which is characterized by the difficulty of assessing environmental impacts from pollution of each emission source, such as determining nutrients leaching into a lake from each surrounding farm. As suggested by Segerson (1988), an efficient outcome can occur if charges on pollution are determined by the environmental impacts from a marginal change in total pollutant load to, for example, a water recipient. Roti Jones and Corona (2008) translated Segerson's result into a uniform charge for changes in the total amount of AIS in a port. As the authors correctly note, this mechanism requires the quantification of changes in invasive species, which can be difficult to obtain in practice.

Conclusions

The purpose of this paper was to present economic analysis and studies on management of invasive species. Two management issues were then raised: how to set targets and how to find the best policy instruments to achieve the targets. Typical for economic approaches is to find the targets that make the best use of society's total resources. This implies the creation of as much social surplus as possible from target setting or, if the damage cost of AIS can not be estimated, achievement of predetermined targets at minimum costs. A three-stage policy intervention scale — prevention and control of spread and damage — was used as a framework for analysis of the two management questions.

Ideally, in setting targets, all three policy levels and associated measures are included when determining social net surplus. For each measure, such as port inspections, creation of barrier zones, or removal of mussels, costs and damage reductions are calculated. This implies the need for recognizing the uncertainty and risk associated with each of the AIS entrance steps into a new region — introduction, establishment, spread, and damage creation — together with the time delays between the implementation of measures and associated impact on damage. This was made in a few theoretical studies where distinctions are usually made between mitigation (prevention and control) and adaptation (damage control or adaptation) measures (e.g. Perrings 2005, Finnoff *et al.* 2005). A relative advantage of adaptation is that resources are focused on reducing real damage, while effects of combating all species spread are more uncertain since not all invasive species create environmental damage. On the other hand, it is usually difficult to control damage from a species once it has been established, which calls for early control or eradication efforts. Other studies point at the importance of timing of measures since the benefits of prevention and control measures depend on the avoided growth rate of the AIS, and also on the need for considering the feedback mechanisms between society and the biological systems (e.g. Olsson and Roy 2002, Finnoff *et al.* 2005). Public policy without this consideration of feedback between the systems may counteract private incentives for combating AIS risks.

Most of the studies aimed at identifying efficient policies for achieving predetermined targets analyse the potential of tariffs on trade and compare this with inspection of imports, which is much used in practice (Costello and McAusland 2003, McAusland and Costello 2004, Knowler and Barbier 2005, Margolis 2005, Tu *et al.* 2005, Tu and Beghin 2006, Batabyal 2007). Another common feature of the studies is that they compare policies with respect to efficiency, i.e. which policy generates the largest social net surplus. An important result from these studies is that a tariff on imports may have counteractive effects and may, in fact, result in higher risk for AIS. This result emerges from the recognition that AIS establishment and damage depend not only on trade volume but also on habitat characteristics in the host country. A tariff reduces imported goods and thereby the infestation rate, but can also increase domestic production of the goods in question, which, in turn, can increase the area of disturbed land and make the country more susceptible to invasion. Inspection policy has the advantage of not raising prices of all imports, but only on the goods rejected. In order to avoid negative side effects from eventual increase of domestic production of rejected imported goods, a tariff reduction could be optimal. This result points at the need for designing the two policies simultaneously, but also addressing the difficulty associated with different public bodies having discretion for their implementation.

In spite of the difficulties of introducing tariffs on trade in practice due to the WTO regulations on equal treatment of foreign and domestic goods, there are relatively few studies comparing different policies for national control of spread and damage of AIS (Thomas and Randall 2000, Jetter *et al.* 2003, Horan and Lupi 2005, Roti Jones and Corona 2008). A common result from this literature is that economic instruments are preferred to command and control policies due to the cost effectiveness property. One such innovative policy is a market for trading in risk suggested by Horan and Lupi (2005), who showed that the system achieves a certain probabilistic risk target at considerably lower cost than technology requirement, which is often used in practices such as ballast cleaning requirement. However, none of the studies analyse or calculate transaction cost of different policy instruments, which can be significant. For example, transaction costs of a wildlife enhancement schemes in UK correspond to approximately 110 per cent of the management cost (Falconer and Saunders 2002).

Although this review has not been exhaustive with respect to inclusion of economic studies of alien species, it reveals that the number of studies is small as compared with that in other fields of environmental concern, such as climate change, biodiversity and water pollution (e.g. Perrings *et al*. 2000). In spite of this, there has been a recent and rapid development of applications of up-to-date theoretical methods on AIS management, which have resulted in important insights for target setting and policy design. However, policy instruments are compared mainly with respect to cost-effectiveness, and not according to other criteria such as certainty in achieving the targets, equity when all firms are subjected to the same requirement or inspection, and transaction cost. Since these criteria may justify the commonly used command and control policy in practice, there might be a bias in the results in favour of market-based instruments.

Analyses of the potential of international agreements are also lacking, but can be very fruitful when considering the role of international trade for spread of AIS (*see* e.g. Stoett 2007, for a discussion on the potential of international agreements). Furthermore, there is a lack of empirical case studies where the achieved theoretical insights have been tested or where actual policies have been evaluated and compared with respect to several criteria. The few studies that exist are mainly applied to US conditions (e.g. Horan and Lupi 2005, Saphores and Shogren 2005). One important reason for the lack of empirical studies is the specific difficulty of obtaining data of sufficient quality on the environmental impacts of potential AIS. This, in combination with the relatively recent concern and policies against AIS, can explain why the economics of alien invasive species is in a relatively early state of research, where several empirical challenges need to be addressed. These involve quantification of direct and indirect impacts of specific species, quantification of impacts of different measures on spread of AIS, improved understanding of the causes for spread of AIS, cost effectiveness analysis of several different prevention and control measures, and better knowledge of the potential of international agreements for combating AIS and of functioning of regulations in practice.

Acknowledgements: I am much indebted to the Swedish Environmental Protection Board for providing funding within the AquAliens research programme, and to two anonymous referees and the editor of Boreal Environmental Research for very valuable comments. The usual disclaimer applies.

References

Anaman K., Atzeni M., Mayer D. & Walthall J. 1994. Economic assessment of preparedness strategies to prevent the introduction of the permanent establishment of screwworm fly in Australia. *Preventive Veterinary Medicine* 20: 99–111.

Bangsund D.A., Leistritz F.L. & Leitch J.A. 1999. Assessing economic impacts of biological control of weeds: the case of leafy spurge in northern Great Plains of the United States. *Journal of Environmental Management* 56: 35–42.

Batabyal A. & Nijkamp P. 2005. On container versus time based inspection policies in invasive species management. *Stoch. Environ. Res. Risk Assess.* 19: 340–347.

Batabyal A. 2007. International aspects of invasive species management: a research agenda. *Stoch. Environ. Res. Risk Assess.* 21: 717–727.

Born W., Rauschmayer F. & Bräuer I. 2005. Economic evaluation of biological invasions — a survey. *Ecological Economics* 55: 321–336.

Burnett K., Kaiser B., Pitafi B. & Roumasset J. 2006. Prevention, eradication and containment of invasive species: Illustrations from Hawaii. *Agricultural and Resource Economics Review* 35: 63–77.

Buhle E., Margolis M. & Ruesink J. 2005. Bang for buck: cost-effective control of invasive species with different life histories. *Ecological Economics* 52: 355–366.

Cembali T., Folwell R., Wandschneider P., Eastwell K. & Howell W. 2003. Economic implications of a virus prevention program in deciduous tree fruits in the US. *Crop Protection* 22: 1149–1156.

Costello C. & McAusland C. 2003. Protectionism, trade and measures of damage from exotic species introduction. *American Journal of Agricultural Economics* 85: 964–975.

Dalmazzone S. 2000. Economic factors affecting vulnerability to biological invasions. In: Perrings C., Williamson M. & Dalmazzone S. (eds.), *The economics of biological invasions*, Edward Elgar, Cheltenham UK, pp. 17–30.

Deangelo G., Batabyal A. & Kumar S. 2006. On economic-cost minimization versus biological-invasion damage control. In: Oude Lansink A. (ed.), *New approaches to the economics of plant health*, Springer, the Netherlands, pp. 23–37.

Eisworth M. & van Kooten C. 2002. Uncertainty, economics, and the spread of invasive plant species. *American Journal of Agricultural Economics* 84: 1317–1322.

Ellsberg D. 1961. Risk, ambiguity, and the savage axioms, *Quarterly Journal of Economics* 75: 643–669.

Falconer K. & Saunders C. 2002. Transaction costs for SSSIs and policy design. *Land Use Policy* 19: 157–166.

Finnoff D., Shogren J., Leung B. & Lodge D. 2005. The importance of bioeconomic feedback in invasive species management. *Ecological Economics* 52: 367–381.

Finnoff D., Shogren J., Leung B. & Lodge D. 2007. Take a risk: preferring prevention over control of biological invaders. *Ecological Economics* 62: 216–222.

Helfand G., Beck P. & Maull T. 2002. The theory of pollution policy. In: Mäler K.-G. & Vincent J. (eds.), *Handbook of environmental economics*, vol. I, North-Holland, Amsterdam, the Netherlands, pp. 251–303.

Horan R.D., Perrings C., Lupi F. & Bulte E. 2002. Biological pollution prevention strategies under ignorance: the case of invasive species. *American Journal of Agricultural Economics* 84: 1303–1310.

Horan R. & Lupi F. 2005. Tradable risk permits to prevent future introductions of invasive alien species into the Great Lakes. *Ecological Economics* 52: 289–304.

IUCN 2000. *IUCN guidelines for the prevention of biodiversity loss caused by alien invasive species*. IUCN council, Gland, Switzerland, February.

Jetter K., DiTomaso J., Drake L., Klonsky K., Pitcairn M. & Sumner D. 2003. Biological control of yellow starthistle. In: Sumner D. (ed.), *Exotic pests and diseases: biology and economics for biosecurity,* Iowa State University Press, Ames, pp. 225–241.

Kahneman D. & Tuersky A. 1979. Prospect theory: an analysis of decision under risk. *Econometrica* 47: 263–291.

Kataria M. 2007. A cost-benefit analysis of introducing non-native species: the case of signal crayfish in Sweden. *Marine Resource Economics* 22: 15–28.

Keller R.B., Lodge D.M. & Finnoff D.C. 2007. Risk assessment for invasive species produces net bioeconomic benefits. *Proceeding of the National Academy of Sciences of the United States* 104: 203–207.

Knight F.H. 1921. *Risk, uncertainty, and profit*. Phoenix Books, University of Chicago Press.

Knowler D. & Barbier E. 2005. Importing exotic plants and the risk of invasion: are market-based instruments adequate? *Ecological Economics* 52: 341–354.

Leung B., Lodge D., Finnoff D., Shogren J., Lewis M. & Lambert G. 2002. An ounce of prevention or a pound of cure: bioeconomic risk analysis of invasive species. *Proc. R. Soc. Lond. B* 269: 2407–2413.

Lovell S.J., Stone S. & Fernandez L. 2006. The economic impacts of aquatic invasive species: A review of the literature. *Agricultural and Resource Economics Review* 35: 195–204

Margolis M., Shogren J. & Fisher C. 2005. How trade policies affect invasive species control. *Ecological Economics* 52: 305–313.

MacLeod A., Head J. & Gaunt A. 2004. An assessment of the potential economic impact of *Thrips palmi* on horticulture in England and the significance of a successful eradication campaign. *Crop Protection* 23: 601–610.

McAusland C. & Costello C. 2004. Avoiding invasives: trade-related policies for controlling unintentional exotic species introductions. *Journal of Environmental Economics and Management* 48: 954–977.

McConnachie A.J., de Wit M.P. & Byrne M.J. 2003. Economic evaluation of the successful biological control of Azolla filiculoides in South Africa. *Biological Control* 28: 25–32.

Moffitt J. & Osteen C. 2006. Prioritizing invasive species: Threats under uncertainty. *Agricultural and Resource Economics Review* 35: 41–51.

Moffitt J., Stranlund J., Field B. & Osteen C. 2007. Robust inspection for invasive species with a limited budget. In: Oude Lansink A. (ed.), *New approaches to the economics of plant health*, Springer, the Netherlands, pp. 7–22.

Mumford. J.D. 2002. Economic issues related to quarantine in international trade. *European Review of Agricultural Economics* 29: 329–348.

Olson L. & Roy S. 2002. The economics of controlling a stochastic biological invasion. *American Journal of Agricultural Economics* 84: 1311–1316.

Olson L. 2006. The economics of terrestrial invasive species: a review of the literature. *Agricultural and Resource Economics Review* 35: 178–194.

Perrings C., Williamson M. & Dalmazzone S. (eds.) 2000. *The economics of biological invasions*. Edward Elgar, Cheltenham UK.

Perrings C., Williamson M., Barbier E., Delfino D., Dalmazzone S., Shogren J., Simmons P. & Watkinson A. 2002. Biological invasion risks and the public good: an economic perspective. *Conservation Ecology* 6(1): 1 [online] URL: http://www.consecol.org/vol6/iss1/art1/

Perrings C. 2005. Mitigation and adaptation strategies for the control of biological invasions. *Ecological Economics* 52: 315–325.

Pimentel D., McNair S., Janecka J., Wightman J., Simmonds C., O'Connell C., Wong E., Russel L., Zern J., Aquino T. & Tsomondo T. 2001. Economic and environmental threats of alien plant, animal, and microbe invasions. *Agriculture Ecosystems & Environment* 84: 1–20.

Pimentel D., Zuniga R. & Morrison D. 2005. Update on the environmental and economic costs associated with alien-invasive species in the United States. *Ecological Economics* 52: 273–288.

Rockwell H.W. 2003. *Summary of a survey of the literature on the economic impact of aquatic weed*. Available at http://www.aquatics.org/pubs/economics.htm.

Roti Jones K. & Corona J.P. 2008. An ambient tax approach to invasive species. *Ecological Economics* 64: 534–541.

Saphores J.-D. & Shogren J. 2005. Managing exotic pests under uncertainty: optimal control actions and bioeconomic investigations. *Ecological Economics* 52: 327–339.

Segerson K. 1988. Uncertainty and incentives for nonpoint pollution control. *Journal of Environmental Economics and Management* 15: 87–98.

Settle C. & Shogren J. 2002. Modelling native-exotic species within Yellowstone Lake. *American Journal of Agricultural Economics* 84: 1323–1328.

Sharov A. 2004. Bioeconomics of managing the spread of exotic pest species with barrier zones. *Risk Analysis* 24: 879–892.

Stoett P. 2007. Counter-bioinvasion: conceptual and governance challengers. *Environmental Politics* 16: 433–452.

Stutzman S., Jetter K. & Klonsky K. 2004. *An annotated bibliography on the economics of invasive plants*. Avalable at http://aic.ucdavis.edu/research1/economics_of_invasive_plants.pdf.

Surkov I., Oude Lansink A., van der Werf W. & van Kooten O. 2006. Designing optimal phytosanitary inspection policy — a conceptual framework and an application. In: Oude Lansink A. (ed.) *New approaches to the economics of plant health*. Springer, the Netherlands, pp. 39–54.

Thomas M. & Randall A. 2000. Intentional introduction of nonindigenous species: a principal-agent model and protocol for revocable decisions. *Ecological Economics* 34: 333–345.

Tu A., Beghin J. & Gozian E. 2005. *Tariff escalation and invasive species risk*. Available at http://econpapers.repec.org/paper/iascpaper/05-wp407.htm.

Tu A. & Beghin J. 2006. *Intra-industry trade, multilateral trade integration and invasive species risk*. Available at http://ideas.repec.org/p/ias/cpaper/06-wp439.html.

Vilà M. & Pujadas J. 2001. Land-use and socio-economic correlates of plant invasions in European and North African countries. *Biological Conservation* 100: 397–401.

Williamson M. 1996. *Biological invasions*. Chapman and Hall, London.